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Rotational Decoupling of Tow Cable Fiber-Optic Transmission Lines at a Winch System

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The use of optical fibers to complement the electrical conductors in the umbilical of a tow cable that interconnects a submarine and an antenna-bearing communication buoy has been considered in two previous reports. This report considers the problem of decoupling the optical fibers from rotational motion encountered at the tow cable winch system. Two methods of decoupling are identified and discussed: (1) an auxiliary transmission line winding device and (2) optical rotary joints complemented with wavelength-divison multiplexing. The advantages and disadvantages as well as the technical considerations of importance of each approach are discussed.

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ROTATIONAL DECOUPLING OF TOW CABLE FIBER-OPTIC TRANSMISSION LINES AT A WINCH SYSTEM

INTRODUCTION

This report discusses two plausible approaches to achieving mechanical decoupling of the fiber-optic transmission lines that exit the umbilical of the tow cable at the winch of the AN/BSQ-5 buoy system. Two previous NRL reports [1, 2] discuss construction of the fiber-optic tow cable and the system aspects of the electro-optical interface.

The AN/BSQ-5 buoy is designed for deployment by military submarines for conducting above-surface radio communications at VLF, LF, MF, HF, and UHF while the submarine is deeply submerged. All uplink and downlink communication and buoy control signals must be passed through the umbilical of the tow cable. All existing systems use electrical conductors for the umbilical; however, optical fibers are being considered for replacing and/or complementing electrical conductors in the umbilical because of their characteristics of small size, large frequency bandwidth, low interline crosstalk, and immunity to pickup of electromagnetic interference. This report assumes the use of optical fibers in the umbilical and discusses two techniques for decoupling the optical fibers from the rotational or twisting motion that occurs at the winch system.

When above-surface radio communications are not required, the buoy is stowed in a nest within the superstructure of the submarine. If its services are needed, the buoy is released from the nest and is paid out with a winch system that stores the excess tow cable on a cylindrical drum. The buoy is towed just beneath the ocean surface, and an antenna is erected to conduct the radio communications. The necessity to mechanically decouple the transmission lines exiting the winch system is illustrated in Fig. 1. The inboard end of the tow cable is usually passed through the wall of the winch drum where the armor is terminated, and the transmission lines are brought out past the axle bearing-blocks through a hollowed out section of the shaft. If the transmission lines were run continuously to the hull penetrators, they would be torn by the rotational motion of the winch drum. This problem is avoided with electrical transmission lines by using a multiple slip-ring assembly. No direct analog to this technique exists for an optical-fiber system.

One obvious method of achieving the decoupling with optical fibers is to perform an optical-to-electrical conversion within the winch drum, followed by electrical transmission of the communication signals through a slip-ring assembly. Beyond the slip-ring the signals could be passed to the radio room electrically or they could be reconverted to optical signals for transmission to the radio room. This approach has been rejected for the following reasons:

- Optical-to-electrical conversion within the winch drum requires that sensitive optical receivers and electrical amplifiers be located within the drum, an area that is difficult to service.

- The high frequency signals that are easily transmitted over optical fibers would be degraded by transfer through electrical slip rings by crosstalk and reflections.

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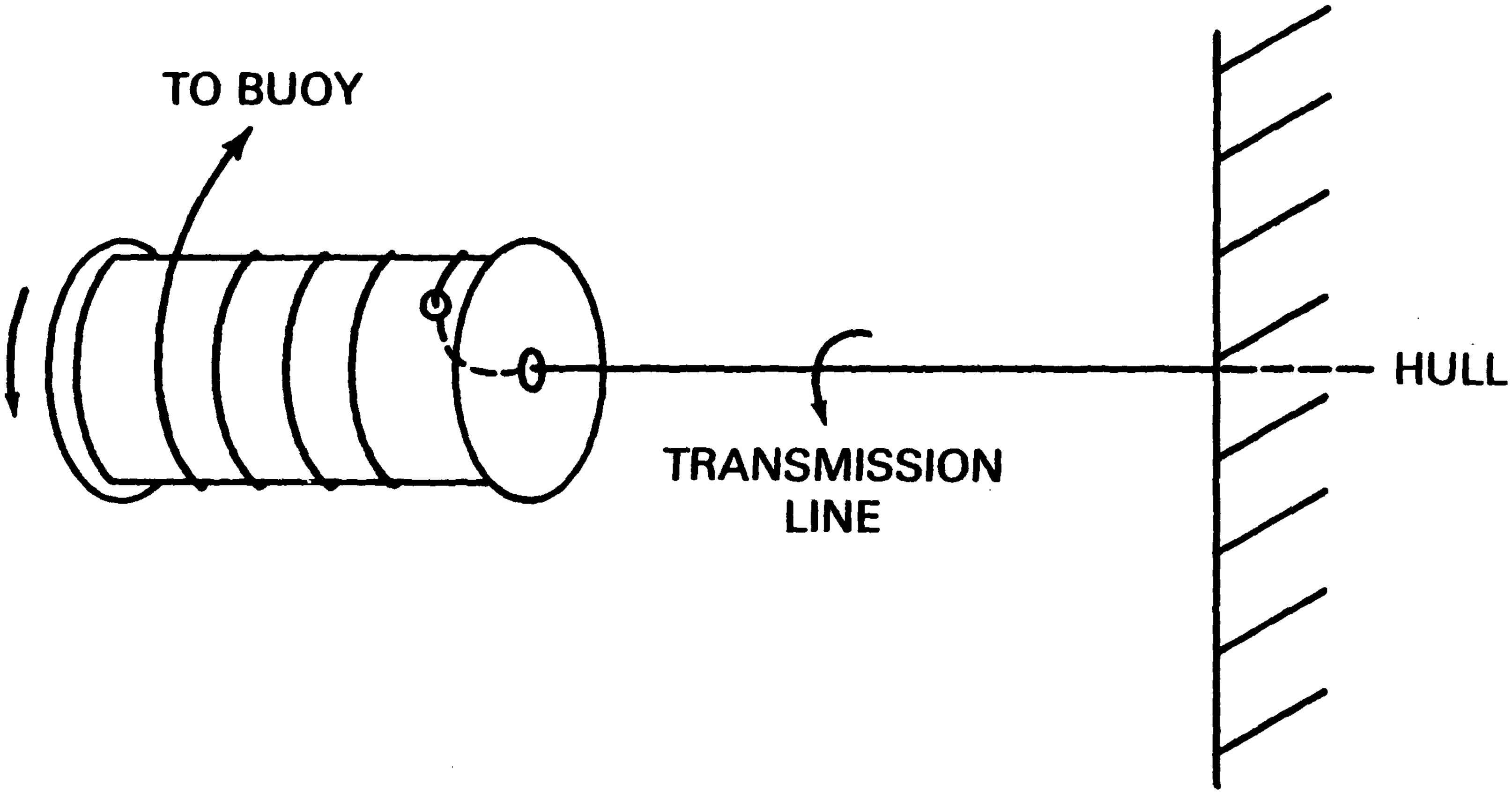


Fig. 1 — Twisting of transmission line caused by rotation of the winch drum

- o Electrical transfer of the communication signals to the radio room is undesirable because of the susceptibility to interference pickup in the relatively noisy environment of the submarine.

- o Electrical-to-optical conversion after the slip rings (instituted to preserve noise pickup immunity) doubles the number of electro-optical conversions, resulting in a significant increase in electro-optical component cost, decreased reliability, and compounded problems with signal distortion and intermodulation crosstalk.

Two attractive alternative approaches to achieving decoupling are (1) the use of an auxiliary cable winder and (2) the use of optical rotary joints. The remainder of the report will be devoted to a discussion of these devices and the special considerations relevant to each.

AUXILIARY CABLE WINDER

An example of an auxiliary cable winder that is manufactured by Fathom Oceanology Ltd., Ontario, Canada is shown in Fig. 2. The motor and pulley assembly to the right of the device functions as a laboratory drive mechanism and should not be considered as part of the device. Typically the winch drum (not shown) would be positioned to the left and coaxial with the shaft of the winder. The rotation of the winch drum provides a 1:1 rotation of the shaft of the auxiliary winder.

The armoring of the tow cable is terminated at the drum, and the electro-optical transmission lines are continued into the interior of the drum and through a hollowed-out channel in the shaft and emerge into the left-hand spool of the winder. After a number of wraps around the spool the fiber cable passes around the transverse sheave, forming a reverse-wound loop, and then wraps with opposite sense of direction around the right-hand spool. The right-hand spool is mounted on the shaft with a slip-sleeve and is secured to a rigid frame, allowing the fiber cable to exit through an opening in the bottom of the right-hand flange free of any twisting action. The left-hand spool is attached to the shaft and rotates with it.

The arm supporting the transverse sheave is mounted in a cradle-shaped hub (see Fig. 3) and slips around the channel as required to maintain tension on the cable. The cradle-shaped hub is free to slip on the shaft but is locked to one or the other spools with a ratchet-pawl assembly (not shown in Fig. 3 but partially visible in Fig. 2) depending upon the sense of shaft rotation. As the winch drum reels the armored tow cable in or out, the transmission line is transfered from one spool of the auxiliary winder to the other. Because of the reverse-wound loop between spools, all twist in the transmission line is eliminated. Since one of the spools rotates at the same rate as the drum and the other does not rotate at all, the length of transmission line required is equal to the product of one half the number of drum revolutions times the mean diameter of the cable stack when contained entirely in one spool. Because the cable tension in the auxiliary winder is limited to that required to rotate the transverse

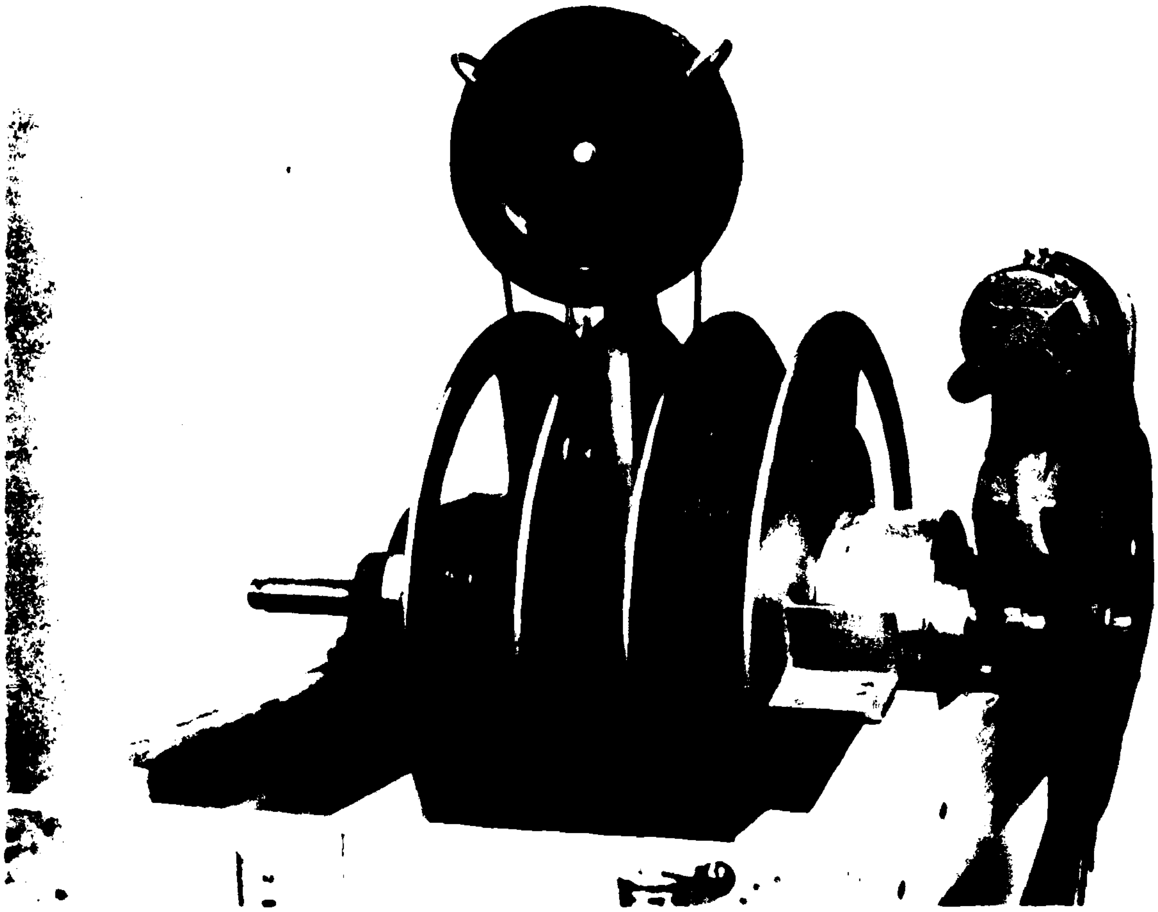


Fig. 2 — Auxiliary cable winder (manufactured by Fathom Oceanology Ltd., Ontario, Canada)

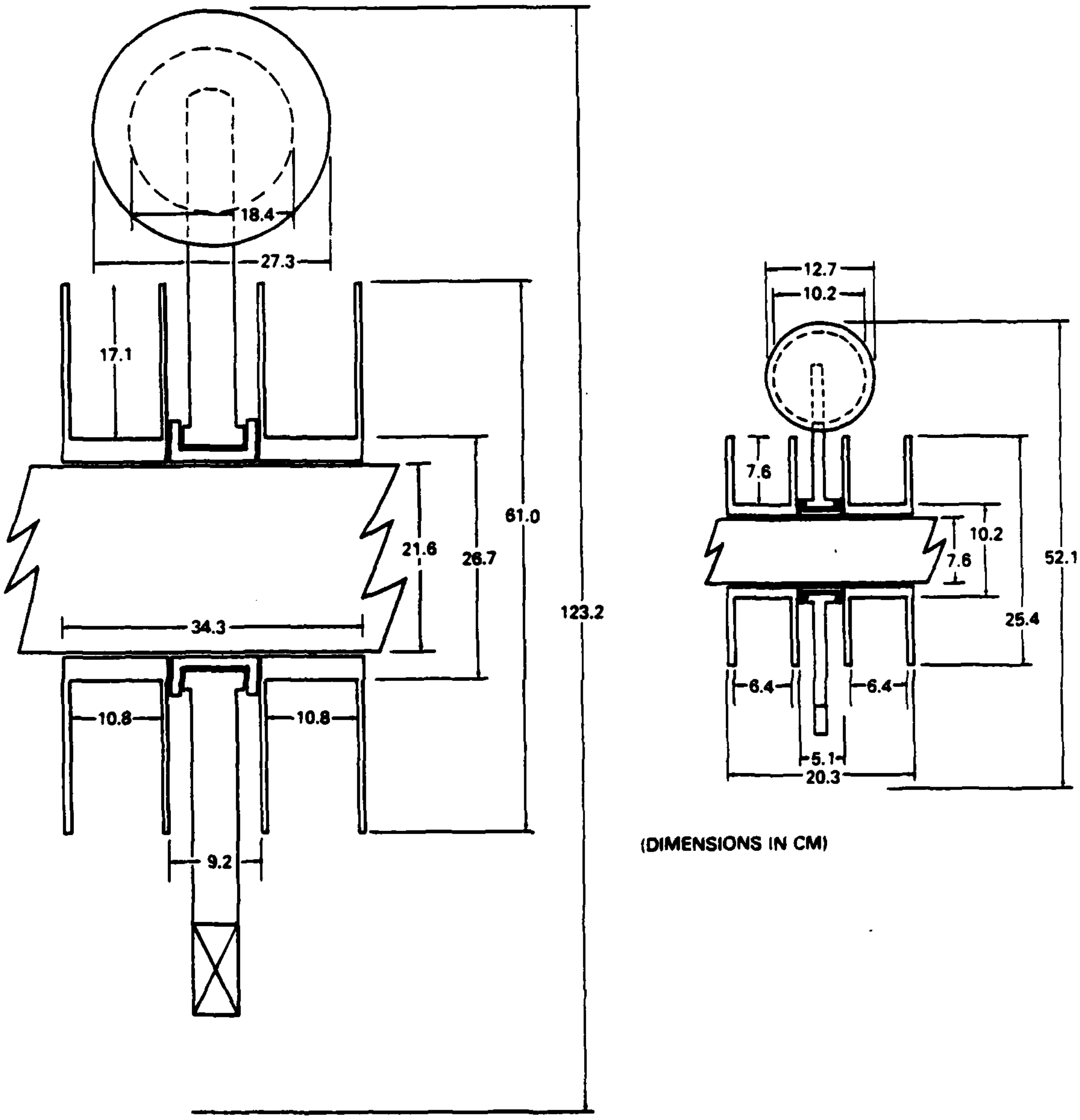


Fig. 3 — Comparison of size of the smallest recommended auxiliary winder (right) to the size of the present Fathom Oceanology device (left)

sheave assembly around the shaft, the strength required of the fiber cable is small and can be achieved easily with a small amount of KEVLAR.

The device shown in Fig. 2 is considerably larger than that required at the winch, but it serves the useful purpose of demonstrating the decoupling principle and identifying problem areas. The following characteristics of the auxiliary winder require modification for successful operation with the AN/BSQ-5 system:

- Size. The clearance diameter required for the device must be reduced to the vicinity of 60 cm or less.

- Noise. The ratchet-pawl assembly is acoustically noisy. Some other mechanism must be developed to lock one side of the cradle-hub to the appropriate spool flange without having the opposite side generate idling noise.

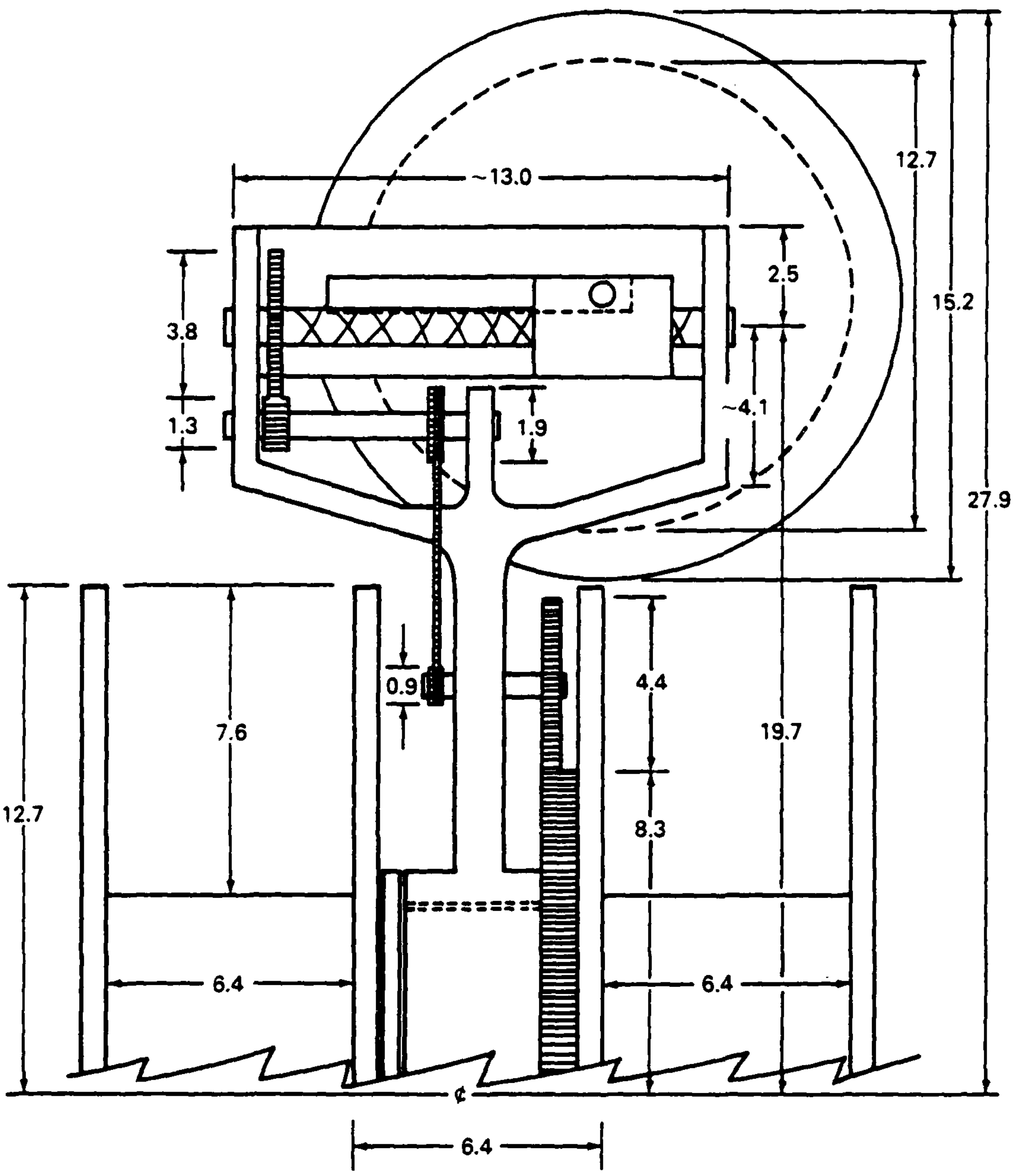
- Cable stacking. The device stacks multiple layers of cable preferentially toward the inside of the spool flanges, leading to eventual stack shifts and slacks in the cable. The design must be modified to improve the stacking of the cable in the spools to insure smooth cable passage around the transverse sheave.

- Hydrodynamic design. The cross-sectional area of the transverse sheave assembly must be minimized in the plane of the sheave to minimize motion impedance in the surrounding fluid (water or oil) medium.

In Fig. 3 a size comparison is presented between the existing Fathom Oceanology winder and what is considered to be the smallest size winder that is recommended. The size of the smaller device was derived by the following reasoning. Wilkins [3] has determined imperically that the smallest recommended radius of curvature for a graded index fiber in a cable structure is about 5 cm if significant microbending losses are to be avoided. This guideline was used to establish the minimum spool diameter of 10 cm. It should be noted, however, that since the fibers are served into the cable structure with a helical lay angle that subjects the fiber to curvature, the wrapping of the cable around a 10 cm diameter spool will result in the bending of localized regions of the fiber with a curvature radius less than 5 cm. This effect will have less significance as the stack height increases.

The volume of the spool was selected so that it would hold 130 turns (equivalent to 260 winch rotations) of fiber cable of 3.55 mm diameter with about 1.6 cm (radial measure) of safety margin on the flange wall height (60% volume fill assumed). The size of the transverse sheave is governed by the separation of the spools and should not have a radius of curvature less than 5 cm. The clearance diameter for the swing of the sheave on the small auxiliary winder is comparable to the diameter of existing winch drums and is therefore in a practical range.

A plausible mechanism for improving the stacking of the cable between the flanges of the spools is shown in Fig. 4. As the transverse sheave



(DIMENSIONS IN CM)

Fig. 4 — Proposed mechanism to stagger the windings on the spools

rotates around the spool flanges an oscillatory lateral motion is provided to the sheave by a helically threaded screw that reverses the sense of pitch at the end of travel. Rotation of the helical screw is derived from gears driven by the relative motion between the sheave-supporting arm and one of the spool flanges and is coupled by a gear and chain drive mechanism having an appropriate reduction ratio. The feed-staggering device cannot lay down the cable optimally in both spools at all times because of the differing stack heights of the cable in each spool. The most satisfactory gearing will be that which provides enough lateral advance to prevent cable crossover for all heights of cable stack. With this choice of gearing many of the layers will have excessive spacing between windings; however, loose windings should not develop, and performance should improve substantially over that without the feed-staggering device.

The objectionable acoustic noise level of the auxiliary winder can be eliminated by replacing the ratchet-pawl device with a one-way roller bearing assembly similar to that manufactured by the Polyclutch Division of Custom Products Corporation. For one sense of rotation the roller bearings of the Polyclutch device lock and prevent relative motion of the bearing journals; for the opposite sense of rotation the journals are free to move.

To minimize the size of the cable for the auxiliary winder (and hence the size of the winder device), it is desirable to include only the optical fibers in this cable. Decoupling of the electrical conductors is achieved most expediently with a slip-ring assembly.

OPTICAL ROTARY JOINTS COMPLEMENTED WITH WAVELENGTH-DIVISION MULTIPLEXING

A second approach to achieving rotational decoupling at the winch system is illustrated in Fig. 5. The discussion of this system begins most conveniently at the winch drum which is illustrated just to the right of center in Fig. 5. The rotation axis of the drum is along a vertical axis in the plane of the paper. An uplink and downlink optical fiber are shown to enter and exit opposite ends of the drum axle. Decoupling from rotational motion is accomplished with an optical rotary joint that preserves optical continuity. Rotary joints using low loss, high bandwidth, multimode single fibers have not been demonstrated but are believed to be within reach of present technology. More discussion on the development of suitable optical rotary joints will follow in the section entitled OPTICAL ROTARY JOINT. After passing through the rotary joints, the two optical fibers are routed through the interior of the drum where they are joined to two optical fibers in the armored tow cable and continue to the buoy.

Eight communication bands of interest from HF to IFF are labeled in the upper left-hand corner of Fig. 5. It is desired to transfer a selected channel received in each of these bands to the shipboard signal processors. A more detailed discussion of these channels and their conditioning prior to the electro-optical conversion is given in [2].

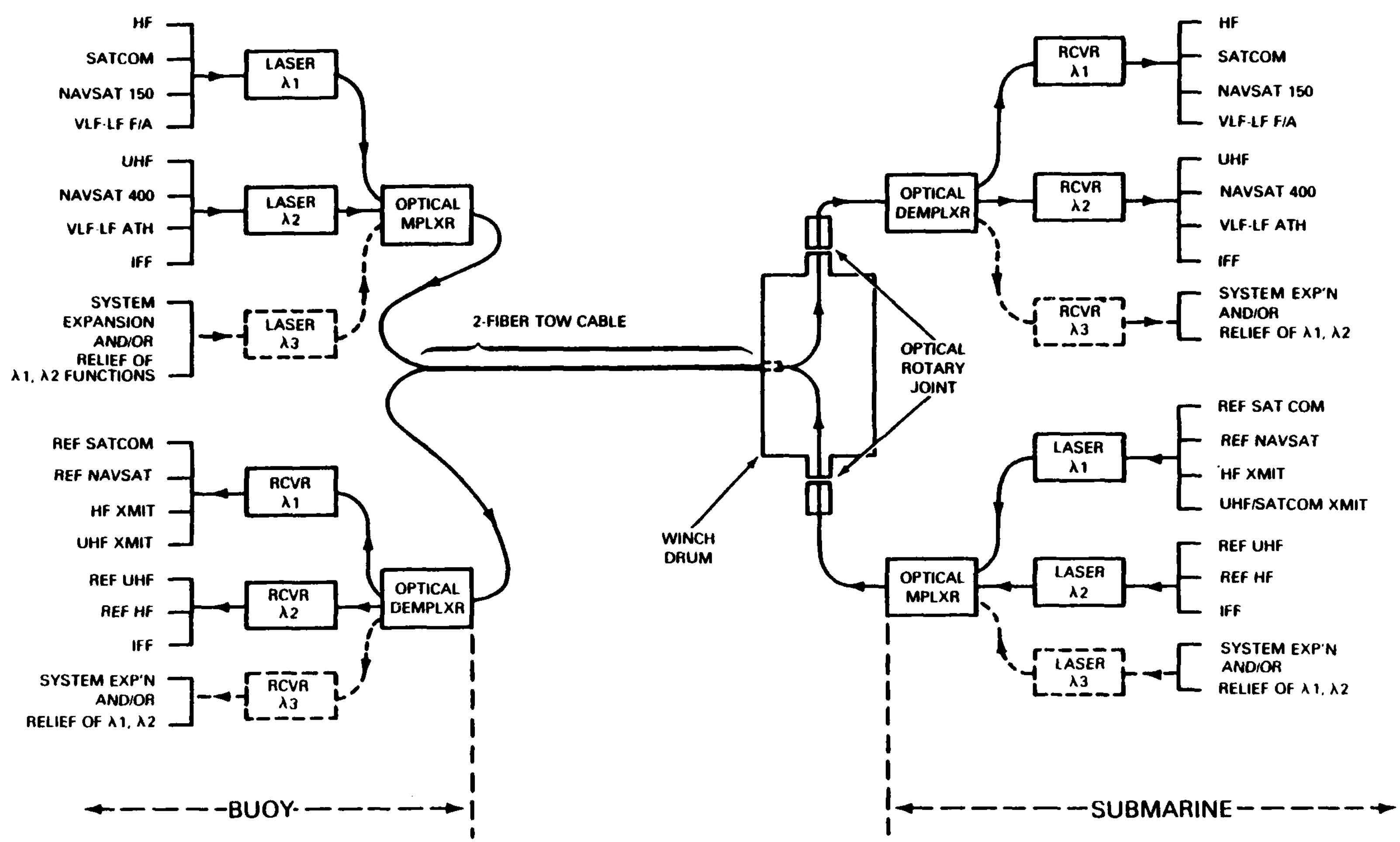


Fig. 5 — Possible design for a rotary joint/wavelength-division multiplexing scheme for a towed buoy communication system

Since the optical power of a source (laser or LED) must be shared (and therefore diluted) among the channels it serves, it is unlikely that a single optical source will provide acceptable performance. The limited linearity of optical sources also restricts the number of carrier frequencies that can be combined to form a composite drive signal for a single optical source because of contamination from harmonic and intermodulation distortion products. Two lasers with different optical wavelengths are proposed for transferring each of two composite groups of four bands to the shipboard system. A third laser at a different optical wavelength is included for future system expansion, transmission channel redundancy, or, if necessary, reduction of the load borne by the other two lasers.

The output of each of the lasers is transported on an optical fiber to the optical multiplexer where all three wavelengths are combined on the single downlink fiber. At the shipboard end of the link the optical demultiplexer puts each wavelength on a separate fiber that connects to the appropriate optical detector. An identically structured system is used for the submarine-to-buoy uplink which carries reference frequencies to the buoy mixers (frequency converters) and modulated carriers to be radiated at the buoy antenna.

One major weakness of the system presented in Fig. 5 is that if the downlink fiber is broken, the entire receiving system will fail; if the uplink fiber is broken, all receiving systems that require reference frequencies (supplied from the submarine in the fiber-optic version of the system) will fail (VLF-LF will continue to operate). A solution to this problem is shown in Fig. 6 where a two fiber redundancy is used in the tow cable for both the up- and downlinks. The price that must be paid for achieving the fiber redundancy in the tow cable is twofold:

- Optical power loss. The combination of the optical splitter and combiner exhibits a minimum overall power loss of 3 dB. This occurs because there is a 3 dB loss of transmitted power though the optical combiner for each of the two inputs. Considering the additional fiber splices required to include the splitter and combiner in the link and less-than-perfect optical coupling in the splitter and combiner, the actual loss to the optical power budget will be 4 to 5 dB.

- Servicing difficulty. Although it should be possible to construct optical splitters and combiners having high reliability, locating these devices inside the winch drum poses definite servicing problems. A possible solution to this problem is to mount these devices on the outside of the drum (perhaps on the end flanges) with an optical fiber penetrating to the interior of the drum and connecting to the rotary joint.

With this system a break in one uplink or downlink fiber will cause a 3 dB loss in the optical power budget but will not cause the link to become inoperable.

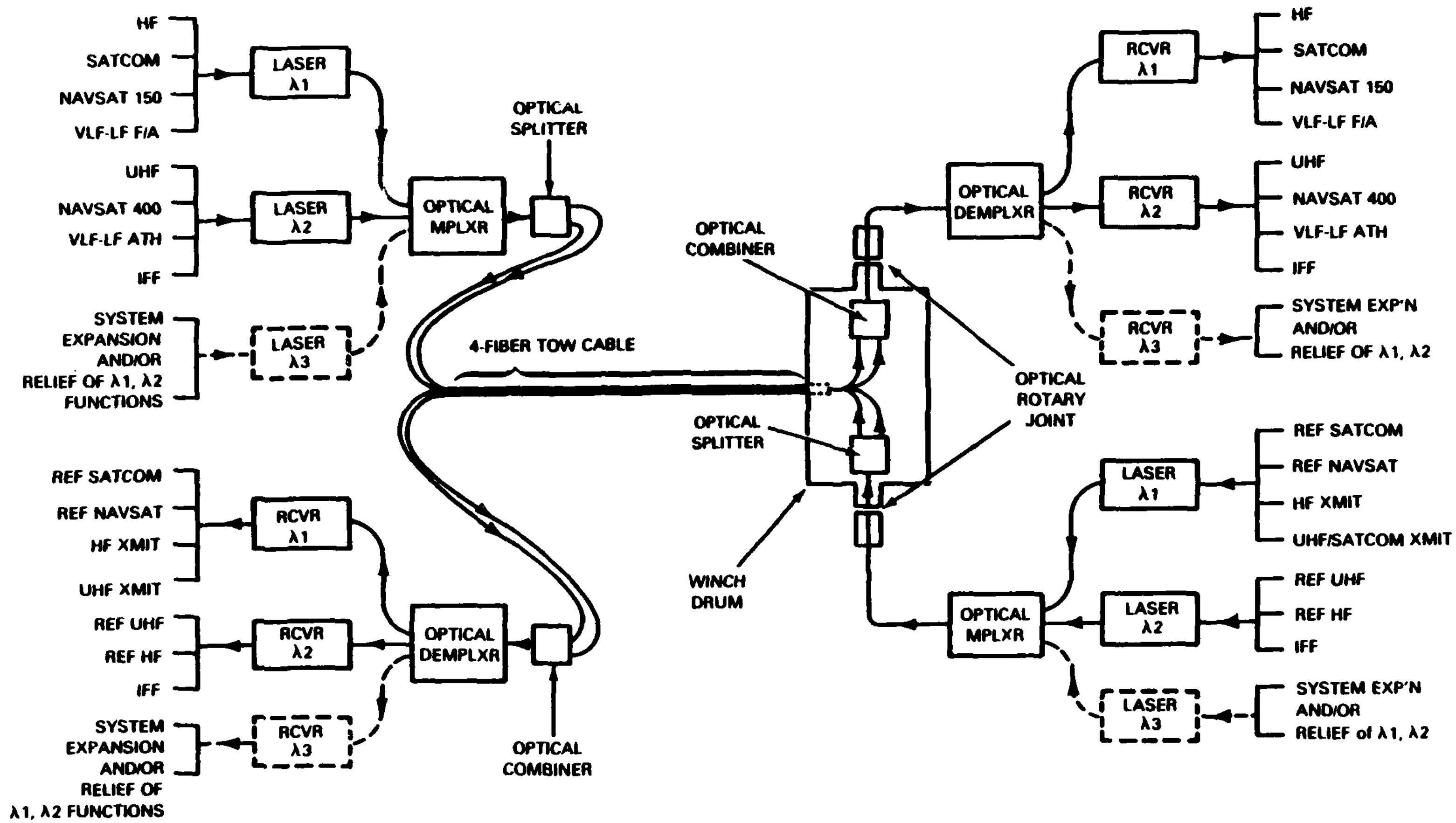


Fig. 6 — Proposed design for a rotary joint/wavelength-division multiplexing scheme exhibiting fiber redundancy in the tow cable

An important consideration that remains to be addressed in the comparison of the two approaches to achieving rotational decoupling is the determination of the optical average power level expected at the optical receiver in each case. This will differ according to the additional link loss contributed by the multiplexer, demultiplexer, splitter, combiner, rotary joint, and additional fiber splices. Estimation of these losses will be deferred until a discussion of multiplexing and demultiplexing is presented in the next sections.

OPTICAL MULTIPLEXERS/DEMULTIPLEXERS

Two practical forms of multiplexers or demultiplexers can be fabricated using either a selective beam splitter or a dispersive element such as a prism or diffraction grating. The principle of selective beam splitting is illustrated in Fig. 7a. Wavelengths λ_1 and λ_2 are incident from the left on a tilted planar element coated with a dielectric material that is reflective at wavelength λ_2 and transmissive at wavelength λ_1. The device can be used as a demultiplexer as shown in Fig. 7a or as a multiplexer by illuminating the device in reverse.

Selective splitters have been constructed with optical fibers by ITT [4] using the approach illustrated in Fig. 7b. The fibers are ground at an angle and the interface is coated with the wavelength selective dielectric. The cladding of the ground fibers is removed in the vicinity of the junction by chemical etching to improve the coupling to the fiber receiving the reflected λ_2 component. The angle at which the end surfaces are ground is usually significantly less than 45 degrees relative to a plane perpendicular to the fiber axis to avoid polarization dependent reflection/transmission properties. The slope of the filter characteristic (transmission vs. wavelength) obtained with this structure is less than that usually specified for the coating material because the uncollimated light incident at the junction smears out the sharpness of the filter characteristic. An improved filter characteristic can be obtained by placing the planar dielectric between collimating and focusing lenses and setting the angle of incidence near zero with respect to the normal to the interface. However, consideration must be given to the increased susceptibility to optical alignment shifts from thermal expansion, vibration, and shock. Susceptibility to change in optical alignment can be reduced by replacing the individual elements with a SELFOC rod assembly as described by Kobayashi et. al. [5].

Crosstalk rejection for the type of selective splitter shown in Fig. 7b for wavelengths of 850 and 1060 nanometers was found to range between 33 and 53 dB [4] depending upon (a) the particular sample tested and (b) whether the construction was for a long-wave-pass or a complementary short-wave-pass device and provided that there was negligible backscatter from the link (backscatter prevented by index matched joints). Optical crosstalk rejection of 30 dB will provide a 60 dB electrical range free of interference provided both wavelengths are launched with equal power and the link loss is the same at both wavelengths. Since decreasing the separation of the wavelengths will further decrease the crosstalk rejection, this form of selective coupler is useful only for relatively wide separation of wavelengths.

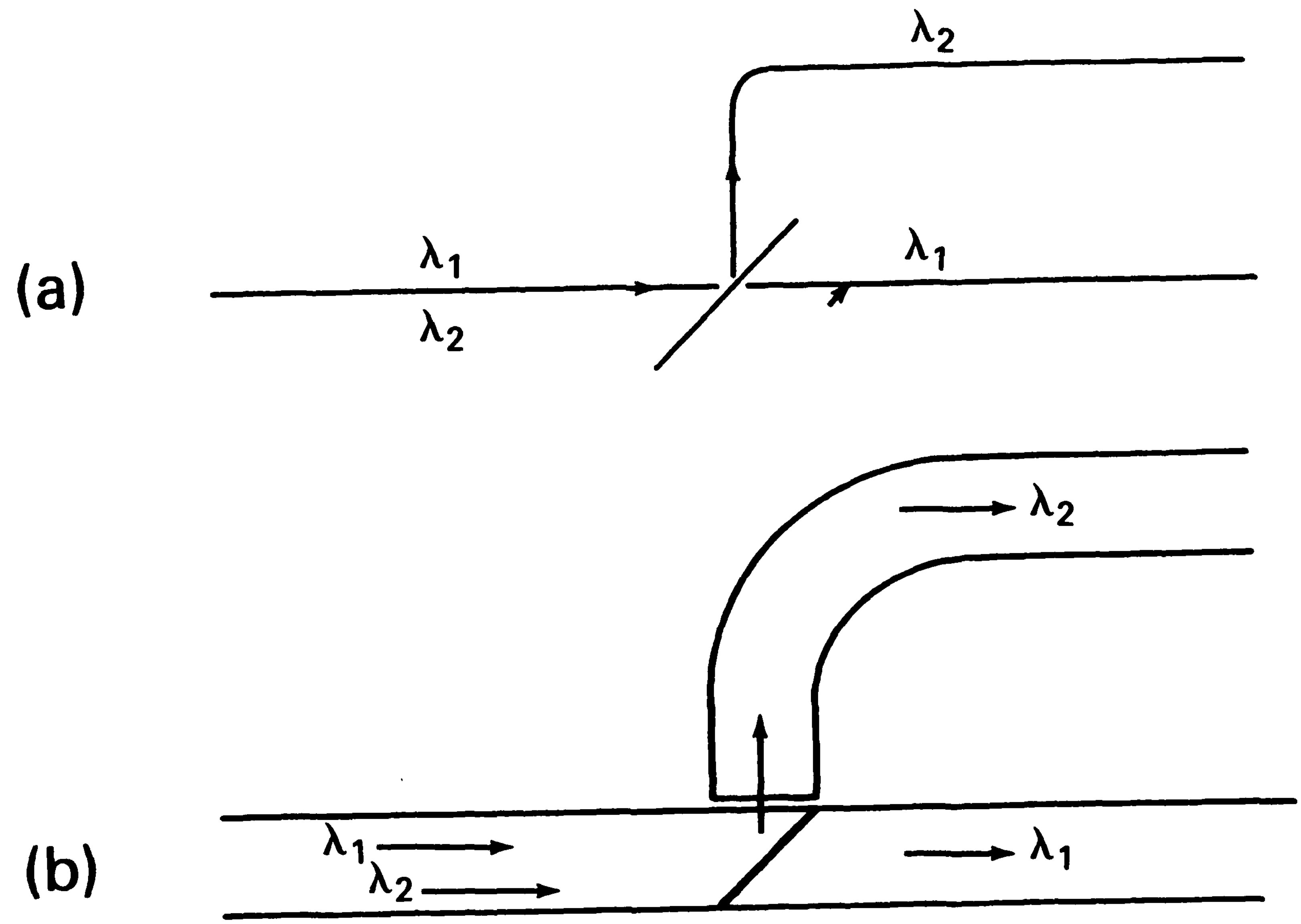


Fig. 7 — Wavelength selective optical splitter or combiner: (a) selective beamsplitter principle, (b) construction of optical fiber selective coupler

Approximate insertion loss for a well constructed device using 55 micrometer core, 125 micrometer outside diameter graded index fiber is about 1.5 dB for the transmission branch and about 2.5 dB for the reflection branch if the device is used as a demultiplexer and the $\lambda 2$ tapoff is 100 micrometer core step index fiber. If the device is used as a multiplexer, for which the λ_2 injection would use 55 micrometer core graded index fiber, the loss for this branch would be higher (numbers not available).

If the power spectrum of each optical source used in the multiplexed circuit is sufficiently narrow so that spectral overlap over the required power range does not occur, wavelength selective multiplexing is not required. Consequently optical combiners can in principle be designed that have an insertion loss of 1/N, where N is the number of sources (4.78 dB loss for 3-λ system). In practice some fraction of a decibel additional loss is experienced. For multiplexers having more than two or three branches, wave-length selecti e couplers should provide smaller insertion loss. Wavelength selective demultiplexers will probably always provide lower insertion loss than will nonselective beam splitters.

The method of achieving multiplexing using a dispersive element is shown in Fig. 8. The link fiber contains wavelengths λ_1, λ_2, and λ_3. The light emanating from the link fiber diverges in accordance with the exit numerical aperture of the fiber and is collimated by a lens. The parallel rays are converted to paraxial rays as they pass through the dispersive medium. The angular separation $\Delta\beta$ of the rays for two different wavelengths is proportional to the difference in wavelength $\Delta\lambda$. The focal length f of the final lens is selected so that the product of f and $d\beta/d\lambda$ (the dispersive constant of the medium) yields the spatial separation necessary to couple the discrete wavelengths to the intended fibers. The most direct physical facsimile of the method of Fig. 8 would be the insertion of a prism for the dispersive medium, all other elements remaining the same. Difficulty in maintaining the optical alignment of the three element system detracts from the utility of this configuration.

It is possible to reduce the number of elements to unity if a concave diffraction grating is used as shown in Fig. 9 as both the dispersive device and the focusing lens. A 10 channel device based on this approach has been constructed and tested by Watanabe et. al. [6]. The multiple wavelength, launching fiber had a graded index profile, 60 micrometer core, and 150 micrometer outside diameter; the receiving fiber had a step index profile, 250 micrometer core, and 300 micrometer outside diameter. The device was tested as a demultiplexer and the large core receiving fibers were used to reduce coupling loss to 2.5 dB per channel. The loss would be higher (numbers not available) if the device were used as a multiplexer because the receiving fiber cannot have a large core and step index profile if the intervening optical link is long and is required to carry high frequencies. When used as a demultiplexer the large core receiving fibers are usually followed immediately by the optical receivers so that little dispersion is introduced.

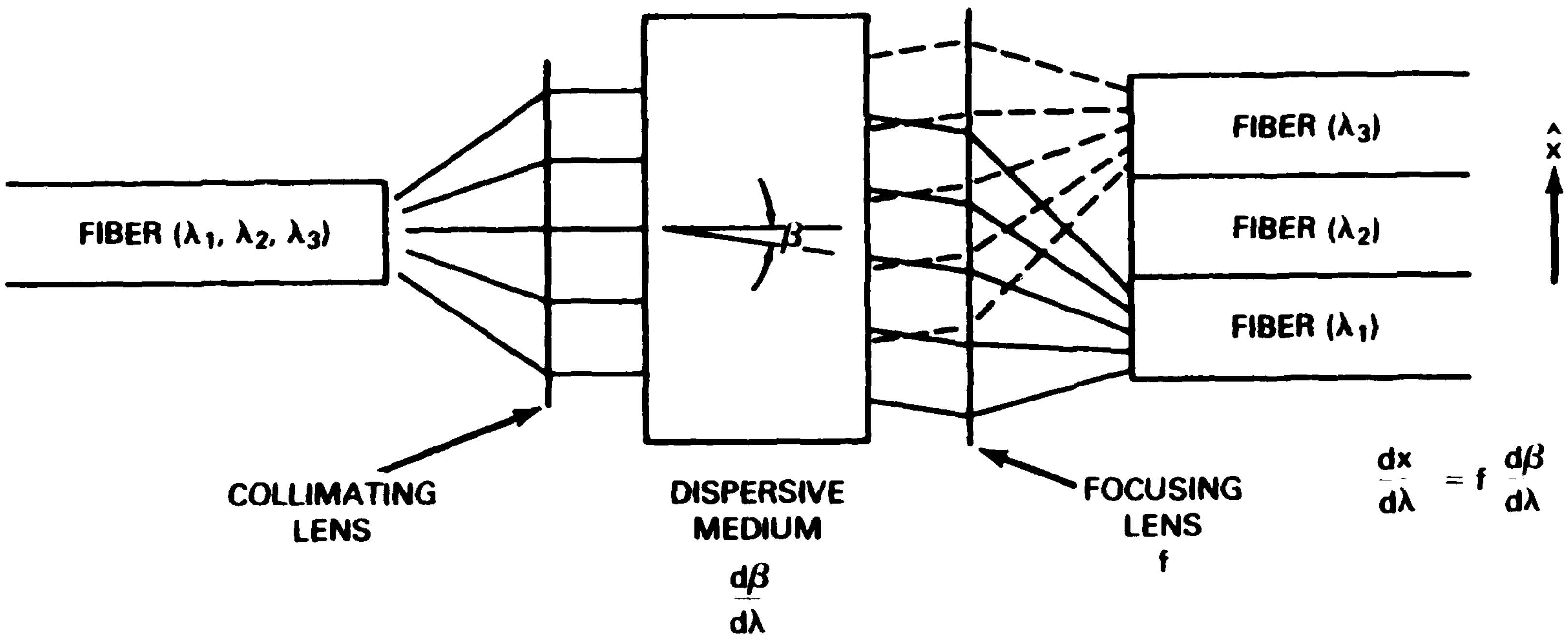


Fig. 8 — Dispersive optical multiplexer or demultiplexer

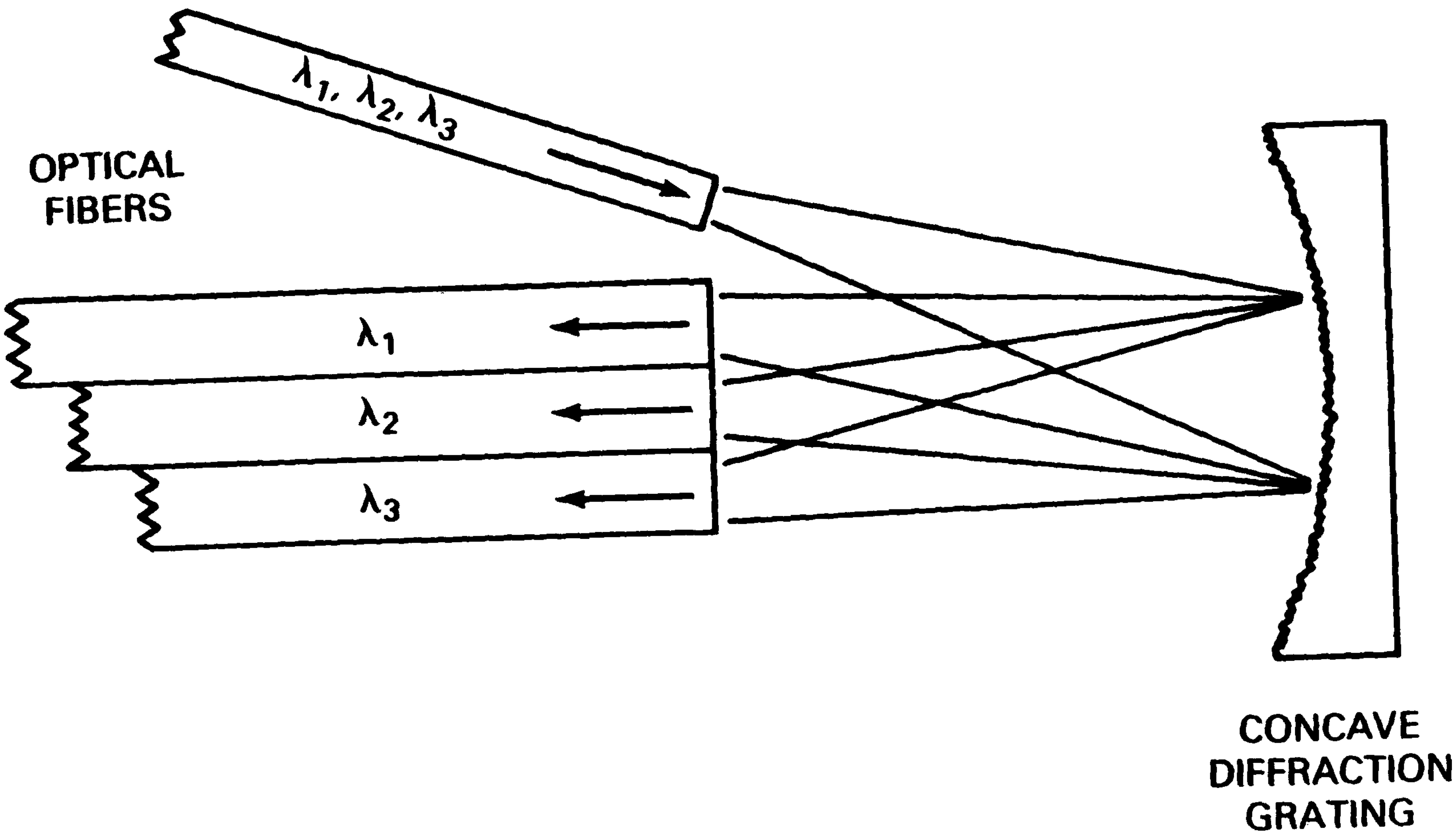


Fig. 9 — Dispersive multiplexer using a combined diffraction grating and reflective lens

The flat passband of the device is about 10 nanometers for each channel. Crosstalk rejection is quoted to be greater than 30 dB at each center wave-length. However, if the source drifts close to the edge of the passband, the crosstalk rejection may be somewhat less than 30 dB. A noteworthy feature of this class of device is that good discrimination is possible between channels spaced only 20 nanometers apart. Additional informative literature on dispersive-type multiplexers is cited in references [7-10].

Spectral width and drift of the laser source must be considered when designing multiplexing hardware suitable for the AN/BSQ-5 towed buoy system. For analog operation single mode lasers are not appropriate sources for multimode fiber links because of inevitable performance degradation from modal distortion and modal noise [11, 12]. This phenomenon can be significantly curtailed if the laser is tailored to exhibit two or more longitudinal modes in its optical spectrum. Many of the presently available GaAlAs lasers have a longitudinal mode line separation of about 0.25 nanometer, resulting in a requirement of a minimum stable spectral bandwidth of 0.5 nanometers for two longitudinal modes.

The spectrum of a laser is known to drift with temperature at a rate of about 0.25 nanometers per degree centigrade. If the laser is thermally mounted to the inside wall of the buoy canister, the extremes in operational temperature may approach 0 to 40 C, resulting in a 10 nanometer spectral shift. Consequently a 10.5 nanometer width plus a suitable safety margin is required for the passband characteristic of the multiplexing system.

Thermoelectric modules [13] can be used to heat and cool the laser chip to restrain the large temperature-associated spectral shift. For General Optronics laser modules, approximately two watts of electrical power are required to lower the laser chip temperature 40 C below the heat sink temperature. The relationship between electrical power and temperature differential is not linear -- the larger ΔT, the less efficient the operation because of internal power dissipation. Consequently, one watt of electrical power is more than adequate to produce 20 C cooling.

Since the thermoelectric module functions as a heat pump, the device can be used to heat the laser by reversing the direction of current flow. Because of internal dissipation the heating mode should be more efficient than the cooling mode; consequently, one watt of electrical power should also suffice to raise the temperature of the laser 20 C. By employing both the cooling and heating modes of the thermoelectric module, the temperature of the laser can be held nearly constant over a heat sink variation of 40 C with a maximum electrical power demand of one watt. One disadvantage of the thermoelectric module is that it acts as a thermal insulator at zero input current; approximately 100 mA is required to maintain a zero temperature differential with the General Optronics laser.

One possible form of a three-wavelength multiplexing system suitable for a 40 C temperature variation (thermoelectric module not used) is shown in Fig. 10. Two lasers near the opposite extremes of the spectrum accessible with GaAlAs lasers (780 and 870 nm) are multiplexed with a diffraction

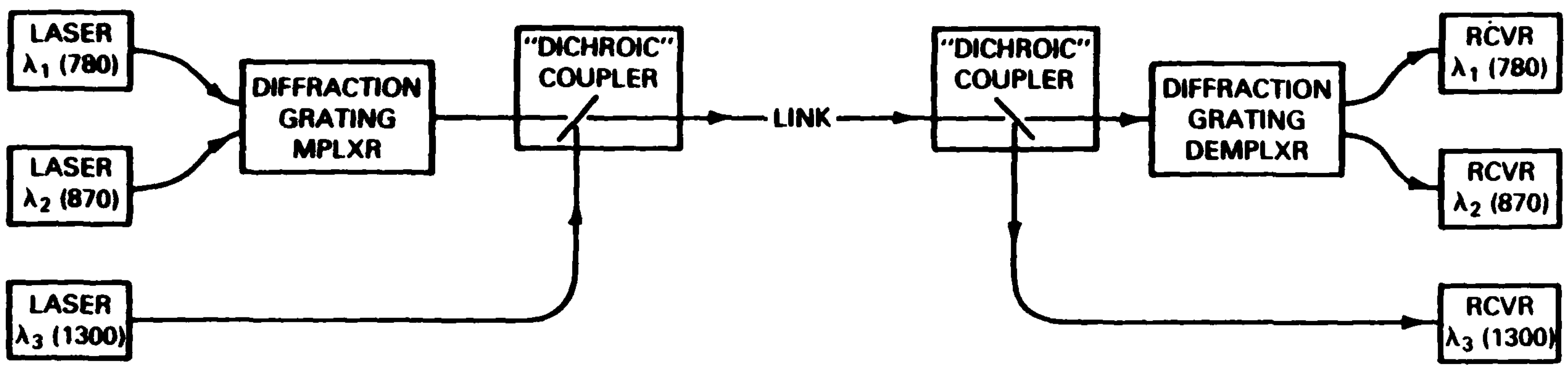


Fig. 10 — Possible design for a three-wavelength multiplexing system when the lasers are not temperature regulated

grating multiplexer. If the insertion loss of the diffraction grating multiplexer exceeds 3 dB, a non-wavelength-selective optical combiner can be used provided the spectral overlap between the lasers (at low power levels) is insignificant. The 90 nm separation in wavelength is sufficient to cope with a 40 C temperature drift for each laser while still retaining small insertion loss at the demultiplexer. A longer wavelength region of 1300 nm is chosen for the third branch where lasers (Hitachi HLP 5000) and photodetectors are presently becoming available. This branch is mutiplexed into the link fiber with a selective beam splitter (dichroic coupler). A dichroic coupler is not appropriate for the 780 nm and 870 nm branch because of the small separation of wavelengths.

The demultiplexing system at the downlink end is essentially the same as the multiplexer with the direction of light propagation reversed. However, a wavelength selective demultiplexer (as opposed to a nonselective 3 dB splitter) must be used for the 780 nm and 870 nm branches to prevent optical crosstalk. Crosstalk rejection should be at east 30 dB optical (60 dB electrical) for all branches.

If the temperature of the lasers in the buoy are controlled, wavelengths for the three branches can be chosen closer together and within the GaAlAs spectral range (750 to 900 nm theoretically, but General Optronics produces only from 780 to 870 nm). Selection of the multiplexing method most appropriate for the AN/BSQ-5 system requires intimate knowledge and experience with the various types of devices. A quantitative tradeoff study should be performed indicating the overall optical loss and crosstalk rejection per branch for each candidate system. The effect of environmental factors of temperature (0 to 40 C) and hydrostatic pressure (0 to 7 MPa) must be considered in the analysis.

OPTICAL ROTARY JOINT

The concept of the optical rotary joint has been introduced previously. In principle a rotating joint can be constructed from some commercially available fiber connectors by modifying the connector shell. Connector designs that employ precision alignment channels such as the interstitial space between glass rods (TRW Optalign connectors) are not well adapted to modification to a rotary joint because the alignment channel must be continuous at the fiber joint and for a considerable distance on each side. Connector designs that achieve fiber alignment from the constriction of a compliant sleeve exhibit a similar incompatability with a rotary joint concept.

An additional design restriction is encountered for rotating connections that is not encountered in static situations: the fibers must remain separated at the joint to prevent scratching of the cleaved or polished fiber ends that would result in an increase of optical loss from additional reflections and scattering. The separation of the fiber ends adds additional insertion loss. Fortunately, of the three independent mechanisms that contribute to connector loss (lateral offset, angular misalignment, and axial offset), axial offset has the least relative significance [14, 15, 16]. It is difficult to quote reliable estimates of the loss experienced for a given offset for each mechanism because the loss depends upon the fiber type (graded or step index), the numerical aperture, and the modal distribution of the light in the emitting fiber. The modal distribution depends upon the optical source used, the launching conditions into the fiber, and the length of fiber between the source and the optical joint.

The loss from axial separation of the fibers can be reduced by using collimating and focusing lenses in the connector with the rotation joint placed in the collimated region. If the emitting fiber could be represented as a point source of light, the fiber would be positioned at the focal point of the collimating lens. Since the light rays would be parallel in the collimated region, the optical system would be insensitive to axial movement at the joint. More importantly, the system is also significantly less sensitive to lateral movement than a conventional fiber-to-fiber joint would be. The improved tolerance to lateral movement occurs because the light can be distributed over the full area of the rotating joint sleeve; whereas, in a ferruled fiber-to-fiber connector (for example, the ITT-Leeds connector) the light is distributed over less than 30% of the ferrule diameter. Consequently, loss caused by deviations from concentricity will be less severe for the lens connector.

In reality the core of the fiber has significant physical dimension; so, the emitting end cannot be accurately represented by a point source. As shown in Fig. 11 the emitting fiber end must be placed outside of the focal point of the collimating lens. In the collimated region the rays are paraxial; that is, the rays are nearly, but not exactly, parallel to the optical axis. Because the rays have some skew in the collimated region, there will be somewhat more sensitivity to axial and lateral misalignment than that expected from the former analysis considering a point source of light at the focal point of the first lens. A quantitative assessment of coupling loss from various types of misalignment requires detailed ray tracing through a specific lens system. Such an analysis should also consider the effect of angular misalignment of the lens from the optical axis. In order to maintain alignment stability between the fiber and the lens, the lens should be in a rod configuration with the fiber permanently attached at one end.

The vertical scale of Fig. 11 has a 4:1 correspondence with the horizontal; consequently, the angular deviation in the collimated region is exaggerated. The cone of rays emanating from the emitting fiber is representative of a numerical aperture of 0.25. The receiving fiber is placed at the image point of the dual lens systems which falls inside the focal point of the second lens.

The focal length of the second lens should be close to that of the collimating lens. If the focal length is increased, the numerical aperture of the focused light will decrease, but the spot size will become larger than the fiber core. If the focal length is decreased, the spot size decreases, but the numerical aperture of the focused light will exceed that of the fiber -- assuming the receiving fiber is identical to the emitting fiber.

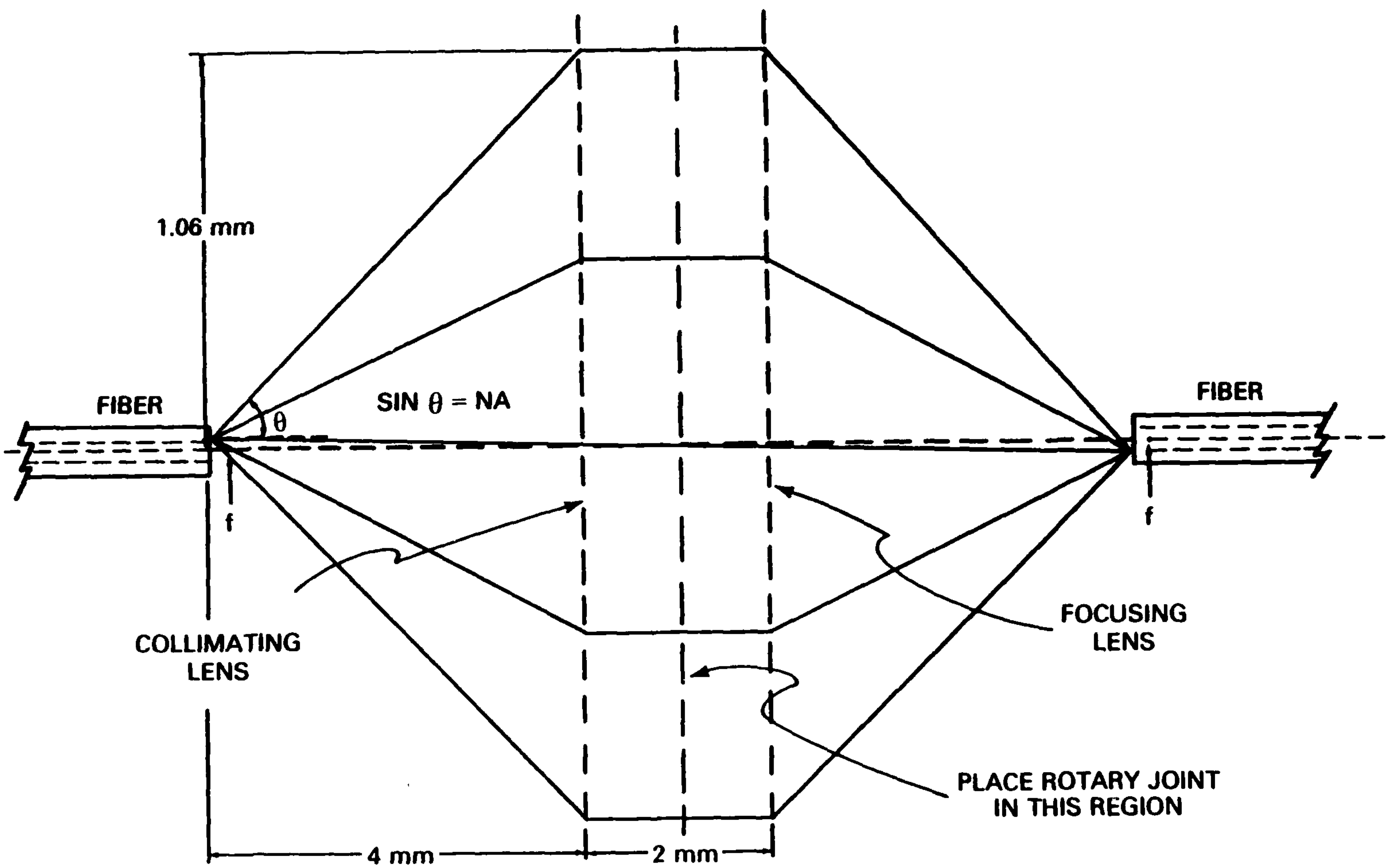


Fig. 11 — Dual lens systems for collimating the optical beam in the vicinity of the rotation joint

To our knowledge a low loss rotary joint has not been developed for single fiber links. It is our opinion that the absence of this development represents a lack of need by the majority of fiber-optics users (telecommunication industry) rather than a lack of the required technological ability.

ESTIMATES OF LINK LOSS: AUXILIARY WINDER VS. OPTICAL ROTARY JOINT

Having completed discussion on all elements of both approaches to achieving decoupling, it is appropriate to conclude with an estimation of total optical link loss corresponding to each approach. Since rotary joints and multiplexing hardware have not been developed, the estimates for that approach represent somewhat of an educated guess. The sources of loss and estimates of magnitude are shown in Fig. 12.

Using the auxiliary winder approach, the sources of loss are the tow cable, auxiliary winder cable (about 70m length), hull penetrator, the link to the radio room (probably less than 30m), and connectors or splices indicated by X's and estimated at 0.5 dB loss each. The overall system loss is about 10.2 dB.

For the decoupling method employing an optical rotary joint and wavelength division multiplexing, significant additional optical losses occur in the multiplexing components, optical splitter/combiner, and rotary joint. The fact that the multiplexer is more lossy than the demultiplexer was established previously. A loss of 4.8 dB was estimated for this device because a non-wavelength-selective three-branch combiner can be fabricated with approximately this loss characteristic. Wavelength-selective devices may have smaller loss. The optical splitter and combiner are each given the characteristic 3 dB loss plus 0.2 dB excess loss for each branch. Since the output of the combiner is increased by 3 dB because of the summing of the two input branches, the overall loss of the combiner is 0.2 dB. The rotary joint is expected to be somewhat more lossy than a conventional static connection; it is anticipated that the loss will not exceed 3 dB. The demultiplexer was assigned a loss of 2.5 dB; this value is consistent with that obtained for the highest loss branch of the ITT dichroic couplers [4] and the dispersive demultiplexers reported by Watanabe et. al. [6] and Aoyama and Minowa [8]. The total loss for this system is estimated to be 27.4 dB.

The large optical loss associated with the rotary joint/wavelength-division multiplexing approach raises some concern for this method. If the laser couples one milliwattt of optical power into the fiber, the power incident at the receiver will be 1.8 microwatts. Since this power is shared by four frequency multiplexed channels, the optical power per information band is about 0.45 microwatts. In many cases this amount of optical power will be expected to provide a 60 dB electrical dynamic range (30 dB optical) at modulation frequencies of 14 to 80 MHz; consequently, careful receiver design must be employed if there is to be a safety margin available in the power budget. Avalanche photodectors may be required. Future availability of higher powered lasers will also help to alleviate the marginal optical power budget for this system.

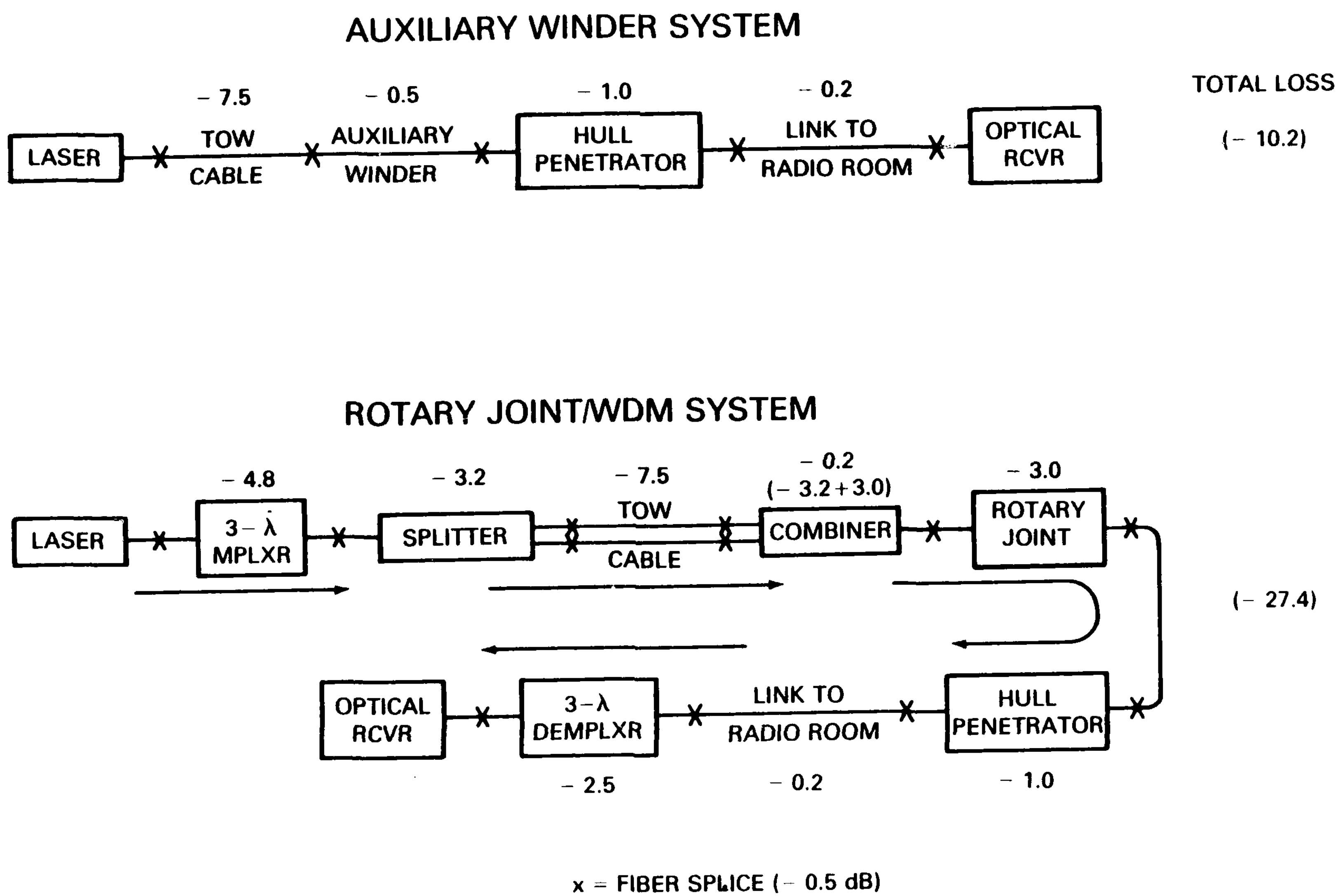


Fig. 12 — Identification of sources and estimation of the magnitude of optical loss for the two approaches to achieving rotational decoupling

SUMMARY

Approaches to achieving rotational decoupling of an optical tow cable at the winch system have been discussed. Two approaches that seem most practical at present are (1) the use of an auxiliary cable winder and (2) the use of two optical rotary joints complemented by wavelength-division multiplexing.

The advantages of using the auxiliary winder are:

- Simple and readily available optical components
- Relatively low overall link loss (10.2 dB estimated)
- Continuous passage of many optical fibers (e.g., eight fibers is reasonable) from the buoy to the submarine.

The disadvantages include:

- Relatively large physical size. Auxiliary winder will require addtional physical space comparable to that occupied by the winch drum on the AN/BSQ-5 system
- Mechanical reliability is not proved. The design of the basic device tested in this study must be changed to achieve better cable stacking, smaller size, and reduced acoustical noise.

The advantages of using optical rotary joints with wavelength-division multiplexing are:

- Small physical size
- Relatively simple mechanical parts. Most complex part will be the optical rotary joint/electrical slip-ring assembly.

The disadvantages include:

- Relatively high overall link loss (27.4 dB estimated)
- Relatively complex optical components required
- A maximum of two optical fibers can be passed through the winch system
- Temperature regulation of the lasers may be required.

One of the purposes of this report was to develop some perspective on the problems and benefits of implementing either method of decoupling. A conclusion as to which method is preferable must be deferred until (a) rotary joint and wavelength-division multiplexing hardware is developed specifically for the buoy system, and (b) an improved auxiliary winder (of reduced size) is constructed and tested.

An attempt is made in the report to give the reader, who is unfamiliar with the subject, an understanding of the technical considerations of importance in the design of an optical rotary joint and wavelength-division multiplexing hardware.

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